Electron Cooling (SF6 & Pelletron) Water System Information

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During the spring 2006 shutdown, two new water cooling systems were added in the E-Cooling Pelletron system in order to aid in stabilizing the temperature fluctuations of both the Magnet Cooling Lines and the SF6 Heat Exchanger system. The electronics (Programmable Logic Controller [PLC] and Operator Interface) for each system where duplicated for both the SF6 & Magnet Cooling Lines in order to simplify the scope of the project. Also, because both systems use the same PLC program and equipment, only one spare system was needed and it is located below the two main units. The main function of the PLC based system is to read back four water temperatures and control one water cooling valve. Both the RTD temperature sensors and the Kammer Control Valve are controlled and read by the PLC using 4-20 mA control signals. Using temperature read backs, the valve position is PLC controlled by an internal Proportional-Integral-Derivative (PID) control loop. If the temperature goes above the set point, the valve opens to allow more cooling water into the system/heat exchanger, thereby lowering the system temperature. If the temperature goes below the set point, then the valve closes to raise the temperature.

The system can be controlled by either the front panel EZText operator interface or the ACNET control system. In order for the data to get transferred from the PLC to ANCET, an Ethernet connection is used, which is controlled by a local application on Node 582. This application reads and writes data to the PLC using dedicated I.P. address. Since only one spare system was built, it was programmed with its own I.P. address, which must be changed in the local application if the spare system is ever used so that the data can correctly read back by ACNET. This can be done by contacting the Controls Group to switch the I.P. address from either the SF6 or Magnet Cooling System over to the Spare station. Either Mike Kucera or Trevor Butler can switch the I.P. address over if something happens to the PLC that causes a failure. Once the address is changed in the control system, the spare system can be brought on-line by simply removing the quick disconnect connectors from the failed system to the operational spare. Note that the Magnet Line Water Cooling System is currently only using two of the four available temperature connectors, so take special care to install the cables to the right locations. Also, since a high degree of accuracy is required in the temperature read backs, make sure that all offsets for the temperature read backs are recalibrated in order to read accurate ΔT's for the system.

The PLC controls the position of the yellow Kammer valve to regulate the amount of cooling water sent to the heat exchanger by use of a PID loop. This loop compares the input temperature of the water flowing to the SF6 heat load or magnet heat load to the set point in order to regulate the position of the valve. When the temperature of the water begins to rise, the PID loop opens the valve to allow more cooling to the system. The general "analog" equation for PID loops is given by the following equation;

$$\text{Control Output} \triangleq M(t) = K_c \cdot e(t) + K_i \cdot \int_{-\infty}^{t} e(\tau)\cdot d\tau + K_r \cdot \frac{\partial e(t)}{\partial t} \qquad \text{where } e(t) \triangleq \text{Process Variable Error}$$

This equation can be broken up into specific terms;

$$\underbrace{M(t)}_{\text{Valve Position}} = \underbrace{K_c \cdot e(t)}_{\text{Proportional Term}} + \underbrace{K_i \cdot \int_{0^+}^{t} e(\tau)\cdot d\tau}_{\text{Integral Term}} + \underbrace{K_r \cdot \frac{\partial e(t)}{\partial t}}_{\text{Derivative Term}} + \underbrace{M(0)}_{\text{Initial Valve Position}}$$

This equation is the ideal equation for analog PID control loops. In order to understand how the discrete PLC calculates the valve position, typically referred to in PID control books as control output; the equation can be simplified. All discrete, non-analog, PID loops sample the process variable (temperature readback) at a defined sample rate T_s. The control output / valve position [M_n] is then calculated using the defined PID loop parameters [K_c, K_i, K_r], the temperature error [e_n] , and the previous valve setting [M_0] for each "n" sample time using the following equation:

$$M_n \triangleq K_c \cdot e_n + K_i \cdot \sum_{i=-\infty}^{n} e_i + K_r \cdot \left(e_n - e_{n-1}\right) = K_c \cdot e_n + K_i \cdot \sum_{i=1}^{n} e_i + K_r \cdot \left(e_n - e_{n-1}\right) + M_0$$

This equation can be broken up into specific terms;

$$\underset{\substack{\uparrow \\ \text{Valve Position}}}{M_n} = \underset{\substack{\uparrow \\ \text{Proportional Term}}}{K_c \cdot e_n} + \underset{\substack{\uparrow \\ \text{Integral Term}}}{K_i \cdot \sum_{i=1}^{n} e_i} + \underset{\substack{\uparrow \\ \text{Derivative Term}}}{K_r \cdot \left(e_n - e_{n-1}\right)} + \underset{\substack{\uparrow \\ \text{Initial Valve Position}}}{M_o}$$

The PID Equation can be further simplified by considering how the PLC calculates the control output for each discrete "n" time step. The table below defines all of the parameters in these equations

$$M_n = K_c \cdot e_n + K_i \cdot e_n + K_r \cdot \left(e_n - e_{n-1}\right) + M_{n-1} = \boxed{\left(K_c + K_i + K_r\right) e_n - K_r \cdot e_{n-1} + M_{n-1}}$$

$$M_{n-1} = K_c \cdot e_{n-1} + K_i \cdot \sum_{i=1}^{n-1} e_i + K_r \cdot \left(e_{n-1} - e_{n-2}\right) + M_0$$

<table>
<tr><th colspan="4">PID Loop Variable</th><th colspan="2">ACNET Parameter</th></tr>
<tr><td>Description</td><td>Sign</td><td>Units</td><td>Range</td><td>SF6</td><td>Magnet</td></tr>
<tr><td>PID Loop Gain</td><td>K_g</td><td></td><td>00.00—99.99</td><td>R:HXGAIN</td><td>R:SWGAIN</td></tr>
<tr><td>PID Integral (Reset) Time</td><td>T_i</td><td>min</td><td>00.00—99.99</td><td>R:HXINTG</td><td>R:SWINTG</td></tr>
<tr><td>PID Derivative (Rate) Time</td><td>T_d</td><td>sec</td><td>00.00—99.99</td><td>R:HXDERV</td><td>R:SWDERV</td></tr>
<tr><td>PID Sampling Rate</td><td>T_s</td><td>sec</td><td>00.00—99.99</td><td>R:HXSMPR</td><td>R:SWSMPR</td></tr>
<tr><td>Process Variable for sampling time n</td><td>PV_n</td><td>°C</td><td>00.00—49.99</td><td>R:HXSF6I</td><td>R:SWMAGI</td></tr>
<tr><td>Set Point for sampling time n</td><td>SP_n</td><td>°C</td><td>00.00—49.99</td><td>R:HXTMPS</td><td>R:SWTMPS</td></tr>
<tr><td>Control Output for sampling time n</td><td>M_n</td><td>%</td><td>00.00—99.99</td><td>R:HXVLSP</td><td>R:SWVLSP</td></tr>
<tr><td>Proportional Gain</td><td colspan="5">$K_c = \pm K_g \times \frac{\text{Valve Fullscale}}{\text{Temp Fullscale}} = \pm K_g \times \frac{100\ [\%]}{50\ [°\text{C}]} = \pm 2 \cdot K_g \left[\frac{\%}{°\text{C}}\right]$</td></tr>
<tr><td>Coefficient of Integral
(Reset) Term</td><td colspan="5">$K_i = K_c \cdot \frac{T_s}{T_i} = 2 \cdot K_g \left[\frac{\%}{°\text{C}}\right] \times \frac{T_s\ [\text{sec}]}{T_i\ [\text{min}]} \times \frac{1\ [\text{min}]}{60\ [\text{sec}]} = \frac{K_g \cdot T_s}{30 \cdot T_i} \left[\frac{\%}{°\text{C}}\right]$</td></tr>
<tr><td>Coefficient of Derivative
(Rate) Term</td><td colspan="5">$K_r = K_c \cdot \frac{T_d}{T_s} = 2 \cdot K_g \left[\frac{\%}{°\text{C}}\right] \times \frac{T_d\ [\text{sec}]}{T_s\ [\text{sec}]} = \frac{K_g \cdot T_d}{2 \cdot T_s} \left[\frac{\%}{°\text{C}}\right]$</td></tr>
<tr><td>Error term for sampling time n</td><td colspan="5">$e_n = SP_n - PV_n\ [°\text{C}]$</td></tr>
</table>

The value of 2 in the Proportional Gain comes from the fact that the control output [$\approx 0-100\ \%$] is not the same scale as the process variable [$\approx 0-50\ ^\circ\text{C}$]. This is because the temperature sensors are only calibrated up to 50°C and because the valve goes from 0 % closed to 100 % open. Both readings are converted to 16 bit uni-polar values internally in the PLC, which created the need for a scaling factor. Since the water system is designed as reverse acting PID loop, the value of K_c is negative since, cooling the water to a ***lower*** temperature requires the valve open setting to increase or get ***higher***.

$$M_n = 2 \cdot K_g \cdot e_n + \frac{K_g \cdot T_s}{30 \cdot T_i} \cdot \sum_{i=-\infty}^{n} e_i + \frac{K_g \cdot T_d}{2 \cdot T_s} \cdot \left(e_n - e_{n-1}\right) \qquad \text{where} \quad e_n = SP_n - PV_n \ \left[{}^\circ\text{C}\right]$$

$$\therefore M_n = 2 \cdot K_g \cdot \left(SP_n - PV_n\right) + \frac{K_g \cdot T_s}{30 \cdot T_i} \cdot \sum_{i=-\infty}^{n} \left(SP_i - PV_i\right) + \frac{K_g \cdot T_d}{2 \cdot T_s} \cdot \left[\left(SP_n - PV_n\right) - \left(SP_{n-1} - PV_{n-1}\right)\right]$$

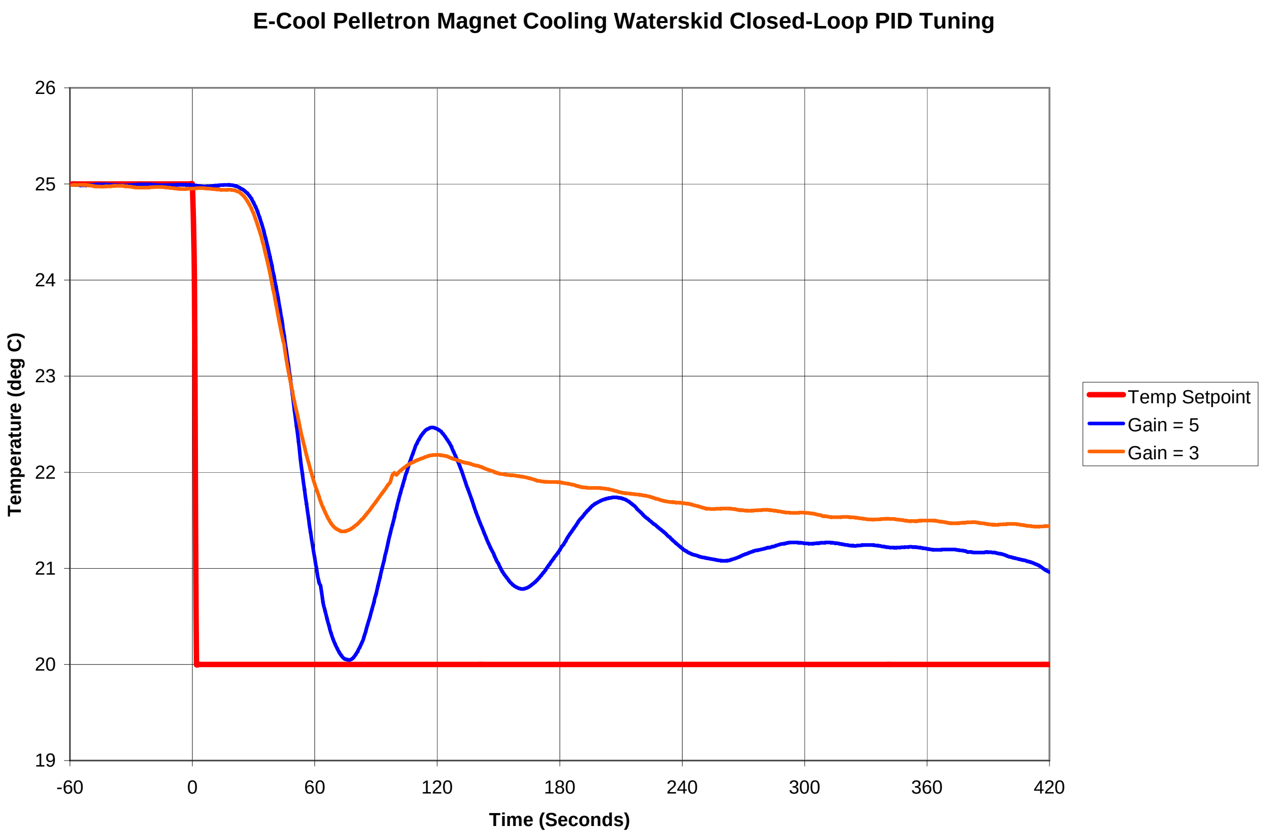
This equation can be broken up into specific terms, which are the actual equations used in the PLC;

$$\boxed{M_n = \left(2 \cdot K_g + \frac{K_g \cdot T_s}{30 \cdot T_i} + \frac{K_g \cdot T_d}{2 \cdot T_s}\right)\left(SP_n - PV_n\right) - \frac{K_g \cdot T_d}{2 \cdot T_s}\left(SP_{n-1} - PV_{n-1}\right) + M_{n-1}}$$

$$M_{n-1} = 2 \cdot K_g \cdot \left(SP_{n-1} - PV_{n-1}\right) + \frac{K_g \cdot T_s}{30 \cdot T_i} \cdot \sum_{i=1}^{n-1} \left(SP_i - PV_i\right) + \frac{K_g \cdot T_d}{2 \cdot T_s} \cdot \left[\left(SP_{n-1} - PV_{n-1}\right) - \left(SP_{n-2} - PV_{n-2}\right)\right] + M_0$$

Determining these PID loop parameters for any given process control system can be daunting task to figure out mathematically without complete system knowledge of all of the leads and lags in the system. In order to define these parameters empirically, equations have been developed that involve collecting data from the system by observing how the complete water cooling system responds to various stimuli, such as changing the position of the water valve or the temperature set point of the system. Using the book ‘Controller Tuning and Control Loop Performance” by David St. Clair, two different techniques where laid out as a guide to tuning any PID control loop. As with any empirical analysis, the values obtained from the tuning techniques are only to be used as a rough estimate of the best PID loop variable settings. Since some systems still require different response curves than those obtained using the following procedures, the system operator is expected have enough system knowledge to change tunable variables to achieve the desire system performance. In many cases, the equations are only used to give the operator some system knowledge and act as a starting point for tuning the system.

The closed-loop tuning procedure/technique is ideal for calibrating the 4 PID parameters while the system is in operation. The main goal of using this procedure is to determine the period at which the system will start to cycle. To do this, the system must first be running in a stable condition. This means that the valve must be operated manually until the temperature of the system can be made stable at it’s normal operating point. In our tuning, we will choose 25°C as our normal operating point. Before the system is switched to automatic tuning, the integral time and derivative time are both set to zero. This will effectively remove their contribution to the valve position and only leave the proportional gain parameter to be adjusted. Once the system has stabilized in temperature, the system is switched to automatic regulation mode. After the switch, the valve position should remain the same if the system temperature read back equals the temperature set point. Using a very small value of Proportional gain, the temperature set point is changed from the normal mode by a few degrees. The system response is then observed and data logged. The goal of this test is to find the point at which the system becomes unstable, thereby operating in an under damped mode. Since any control loop will cycle if the controller gain is made high enough, this test will yield some important information. The gain is increased until the loop starts to oscillate. This point is called the ultimate gain. The system gain should not be set above this value in normal operation. When the gain is raised about the ultimate gain, the system will increase in oscillation until the valve starts going from rail to rail for every temperature change. Since this is not a desired mode of operation, the gain is kept low to prevent this from every happening. This procedure is repeated for different values of gain and was done on the magnet water cooling loop below. It is very important to reduce the temperature dead-band to ***zero*** when collecting this data! Dead-band is only used to eliminate valve jitter when the temperature read back is close to the set point.



From the above graph, there are two very important parameters to note; the period of cycling and the ultimate gain. The PID loop parameters are then roughly calculated using the following equations:

Period of Cycling = P_n

Integral Time = $T_i = \frac{5}{4} P_n$

Ultimate Gain = K_{ug}

Derivative Time = $T_d = \left[\frac{P_n}{8} = \frac{T_i}{10} \right]$

Proportional Gain = $K_g \cong \frac{K_{ug}}{3} \left\{ \frac{K_{ug}}{4} \leq K_g \leq \frac{K_c}{2} \right\}$

Sample Rate = $T_s \ll \left[\frac{P_n}{8} = \frac{T_i}{10} \right]$

Using the above graph, the PID Loop parameters are calculated for the magnet cooling system as:

$P_n \approx 90$ seconds

$K_{ug} \approx 6$

$K_g = 2$

$T_i \approx 2$ minutes

$T_d \approx 12$ seconds

$T_s = 1$ second

Complete Parameter List for Electron Cooling (SF6 & Pelletron) Water System

SF6 WATER COOLING SYSTEM		SILO MAGNET LINE COOLING SYSTEM	
Device Name	***Descriptive Text***	***Device Name***	***Descriptive Text***
R:HXTMPI	HX Water Temp IN	R:SWTMPI	SILO Water Temp IN
R:HXTMPO	HX Water Temp OUT	R:SWTMPO	SILO Water Temp OUT
R:HXSF6I	HX SF6 Temp IN	R:SWMAGI	SILO Mag Loop Temp IN
R:HXSF6O	HX SF6 Temp OUT	R:SWMAGO	SILO Mag Loop Temp OUT
R:HXVLRB	HX Valve Readback	R:SWVLRB	SILO Valve Readback
R:HXVLSP	HX Valve Set Point	R:SWVLSP	SILO Valve Set Point
R:HXTMPS	HX Temp Set Point	R:SWTMPS	SILO Temp Set Point
R:HXTMPD	HX Temp Deadband	R:SWTMPD	SILO Temp Deadband
R:HXGAIN	HX PID Gain	R:SWGAIN	SILO PID Gain
R:HXINTG	HX PID Integral	R:SWINTG	SILO PID Integral
R:HXDERV	HX PID Derivative	R:SWDERV	SILO PID Derivative
R:HXSMPR	HX PID Sample Rate	R:SWSMPR	SILO PID Sample Rate
R:HXOFF1	HXTMPI Offset	R:SWOFF1	SWTMPI Offset
R:HXOFF2	HXTMPO Offset	R:SWOFF2	SWTMPO Offset
R:HXOFF3	HXSF6I Offset	R:SWOFF3	SWMAGI Offset
R:HXOFF4	HXSF6O Offset	R:SWOFF4	SWMAGO Offset

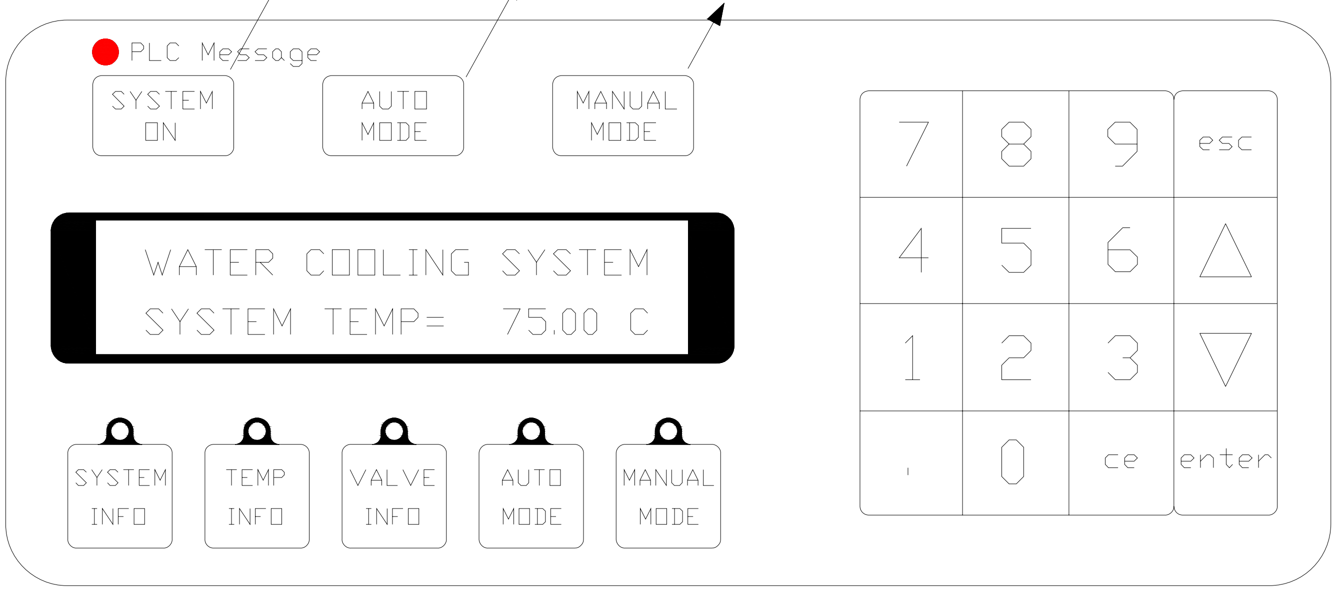
EZText Operator Interface Instructions

LCD Panel Description: The LCD display for each Water Cooling System has 2 modes of operation
Edit Mode → View Temperature/Valve Settings & Read backs. [The *PLC Message* LED not lit when in this mode]
PLC Message Mode → Display general system information. [The *PLC Message* LED will be lit when in this mode]

LCD Panel Operation: To toggle between the Edit Mode & PLC Message Mode, press the **esc** button once, then <u>wait</u> until the *PLC Message* LED light has changed states. When in the Edit Mode, all settings and read backs can be accessed by using the up and down arrows to scroll down to the appropriate folder, press the enter button, then scroll down to the desired device setting/readback. To change any devices settings, such as the Valve Open* setting, scroll down to the appropriate device, press enter once, use keypad to enter in the new setting, then hit enter again. If you make a mistake in the process, press the esc button.

**Note: Valve Open*
Closed= 0% (NO cooling)
Open= 100% (MAX cooling)

<u>SYSTEM ON</u>: PLC has control power and is running is running normally
<u>AUTO MODE</u>: PID Loop is regulating temperature *(Normal Condition)*
<u>MANUAL MODE</u>: PID Loop is NOT!!! regulating temperature



<u>HOW TO OPERATE THE WATER COOLING VALVE MANUALLY</u>

When operating in Auto Mode, the PLC compares the system load input temperature read back to the temperature set point to operate the position of the water cooling regulator valve using a PID control loop. In an emergency, when extra cooling is needed and the PID loop is not responding fast enough, it is desired to override this automatic valve control and manually open the valve. To do this, first make sure that the PLC is in the PLC Message Mode by pressing the **esc** button until the *PLC Message* LED light is on. Once in this mode, press the **MANUAL MODE** button once. If not already displayed on the LCD Display, press the **VALVE INFO** button to display the valve set point & read back. The valve set point can then be changed as desired using the keypad as described above. While in PLC Message Mode, the **SYSTEM INFO & TEMP INFO** buttons can be used to quickly read the system temperature information. In order to put the control system back to normal operation, press the **AUTO MODE** button to return control of the valve set point back to PID temperature regulation loop. Note that the system must *NEVER!!!* be left in manual mode when normally operating the Pelletron